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Estimation of Trafficable Grades from Traction Performance of a Forwarder

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Abstract – Nacrtak

Wood as a renewable resource is getting more and more popular for material use as well as for energy usage. In order to meet the demands, it is important to make previously unused wood potentials accessible to the timber market. One area of interest is the incompletely utilized resources in inclined regions. Problems arise in these areas by the topographic limitations of highly mechanized timber harvesting. These limitations occur from the stability of the machines as well as from the damages done to the soils.

Considerations about the downhill slope forces acting on the machines show a direct relation between the inclination of a grade and the traction coefficient. In theory, it seems possible to calculate a trafficable grade for an accepted level of wheel slip. On the basis of a 25% slip limitation, a model for trafficable grades was developed and tested for typical hillside conditions.

Measurements of traction force vs. slip identified the soil water content and the skeletal rate as the main soil parameters that affect the climbing ability of machines. Test drives in inclined terrain indicated that the approach of calculating limitations (for trafficable grades) from traction tests under level conditions lead to a fairly good prediction.

Keywords: full mechanized harvesting, slope, loess, slip resistance, model

1. Introduction – *Uvod*

In times of a growing demand for renewable energy, forestry in Central Europe copes with an increasing demand for raw timber. On the one hand there are paper and sawmills that utilize timber, whereas on the other hand the request for biomass is increasing rapidly. This leads to an increasing demand particularly for low value timber. Market prices change and first thinnings even under unfavorable conditions generate a positive profit margin. Therefore, a highly mechanized harvesting in smaller stands is requested. The application of harvester and forwarder is beyond dispute under lowland conditions, which results in strong activities in timber mobilization from these areas. In low mountain range the discussion about the permanent conservation of trafficability sets limits to fully mechanized harvesting. The existing certification labels like FSC (Forest Stewardship Council) and PEFC (Program for the Endorsement of Forest Certification) require an appropriate machine usage so that the foresters are well advised to look for valid limitations.

Trafficability of soils is endangered by the driving activities with forest machinery. Damages to soil result from soil compaction and erosion processes. Compaction is especially well investigated for agricultural soils (Blackwell et al. 1986; Bailey et al. 1996; Trautner and Arvidsson 2003, Arvidsson and Keller 2007; Ansorge and Godwin 2007, 2008; Horn and Fleige 2009) as well as for forest soils (Wästerlund 1983; Moffat 1991;Hutchings et al. 2002; Horn et al. 2004; Jun et al. 2004; von Wilpert and Schäfer 2006; Horn et al. 2007). Erosion on the other hand is often seen in conjunction with tillage operations and the opportunities through changing to conservation tillage or to a total abandonment of tillage (Tebrugge and During 1999). Besides tillage, traffic on soils leads to increased risk of erosion (Raper 2005). Podsiadlowski (1988) and Mosimann et al. (2008) focused on the tracks of machines and detected that erosion increased. Bazoffi et al. (1998) showed that reduced tire inflation pressure and therefore better traction of the machines leads to reduced erosion on slopes. In low mountain ranges the problem of soil erosion is enforced by higher rain falls and needs for traction to assure mobility of forest machines. Therefore, soil erosion caused by slip of the wheels is the main risk to a permanent trafficability in inclined terrain.

Results from Söhne (1952) indicate that the risk of serious harm done to the soil increases with increasing slip. High wheel spin leads to a complete shearing-off of the topmost soil structures. Loose soil material gets washed away with the next intense rain. Even for countries with lower requirements to soil protection the long term conservation of technical trafficability as well as the weight of soil as a fundamental factor of production are important. Objective limits for harvesting operations with land-based machinery are important for reducing the additional strain by higher wheel slip. Söhne (1952) found that especially slip levels up to 25% assure a minimum of continuity of the soil pores whereas higher slip leads to a shearing-off of the topmost soil. Particularly, grades are endangered by erosion because of these lost connections between the soil layers. Therefore, slip has to be limited when driving in grades in order to assure long term trafficability (ecological and technical).

The aim of this paper is to present a method to calculate maximum inclination angles for an accepted wheel slip level of 25% as this assures a minimum of continuity of the soil pores (Söhne 1952). Considerations about the downhill slope forces acting on the machines show a direct correlation between the inclination of a grade and the traction coefficient. The latter describes the relation between traction force and machine weight. Measurements of traction force in dependency of slip were taken for a forwarder under different soil conditions in order to oppose them to the downhill slope force at different inclination angles. In theory, it seems possible to calculate a trafficable grade for an accepted level of wheel slip. On the basis of a 25% slip limitation, a model for trafficable grades was developed and tested for typical low mountain range conditions in Germany. In addition, estimation for maximum inclinations with the meaning of safety against sliding down was calculated.

2. Theoretical Approach – *Teorijski pristup*

Every self propelled machine has to produce a traction force (or »thrust«) which overpowers the motion resistance forces. The latter result from aerodynamic resistance (R_a), resistances due to the internal running gear (R_{in}) and resistance due to the interaction between drive line and terrain (R_t), commonly known as rolling resistance (Wong 2010). When driving on slopes, there is an additional grade resistance (R_g), which results

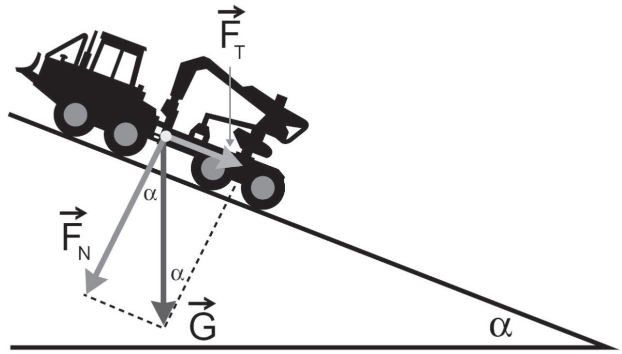

Fig. 1 Forces acting on machines while driving on slopes (Source: Jacke and Drewes 2004)

Slika 1. *Utjecaj sila na vozila na nagibu (Izvor: Jacke i Drewes 2004)*

from the downhill slope force (F_T (N) in Fig. 1) acting on the machines.

Fig. 1 illustrates the forces appearing when driving on grades. The downhill slope force (F_T) is derived from the product of weight of the loaded vehicle (G – gravity force (N)) and the sine of the inclination angle following the equation:

$$F_T = G \times \sin\alpha \quad (1)$$

In order to assure the mobility of a machine, a force at least equal to the downhill slope force has to act in the opposite direction. The force left when the motion resistances (at low speeds this is just the rolling resistance) are overpowered is the traction force (or net traction in Zoz and Grisso 2003). It can be calculated from the traction coefficient (μ_{tr} also called »net traction ratio«) multiplied with the normal force (F_N (N)) acting between the vehicle and terrain.

$$F_d = F_N \times \mu_{tr} \quad (2)$$

Under flat conditions, the normal force (F_N) is equal to the weight (gravity force) of the machine. However, with increasing inclination angle of the slope, the forces differ substantially. The traction coefficient varies with soil properties, drive line of the vehicle and wheel slip. When soil and drive lines are defined, the traction coefficient changes depending on the slip. Typical progressions of the coefficient over slip were studied by numerous authors (Söhne 1952; Wanjii et al. 1997; Yoshida and Hamano 2002; Zoz and Grisso 2003; Hittenbeck 2009; Wong 2010).

$$G \times \sin\alpha = F_N \times \mu_{tr} \quad (3)$$

The comparison between downhill slope force and drawbar pull in equation 3 reveals that the forces for the calculation differ. In order to solve the equation, the normal force of the machine (F_N) has to be expressed as a function of weight (G) and the inclination angle.

$$F_N = G \times \cos\alpha \tag{4}$$

Inserted into equation (3) this leads to:

$$G \times \sin\alpha = G \times (\cos\alpha) \times \mu_{tr} \tag{5}$$

Equation 5 simplifies to:

$$\mu_{tr} = \tan\alpha \tag{6}$$

From this point, the traction coefficient (μ_{tr}) leads to the slope which is barely accessible. The tangent value of the inclination can easily be transformed to slope inclination given in percent by multiplying with 100. As the traction coefficient is closely related to the wheel slip, it is possible to predict the occurring slip values. The general relation between the traction coefficient and the inclination trafficable is not new and it has already been shown by several authors (Pampel 1982; Schulz 1988; Kunze et al. 2002; Hoepke and Appel 2002).

3. Methods and Results – *Metode i rezultati*

3.1 Traction Measurements – *Mjerenje vučnih značajki*

The determination of coefficients of traction was done by traction force vs. slip measurements carried out with a forwarder (Ponsse, model S10) under level conditions. This was done for different variants, which result from different setups of the final drive (worn tires, new tires, reduced tire pressure, combination of tracks and chains) as well as different soil types and varying soil moisture content. In addition to measurements with an empty forwarder, a few variants were tested for a loaded machine as well.

A special winch was constructed to apply different loads to the forwarder for the traction tests. The winch is linked to a breaking system from a heavy truck. Both were mounted to a platform in order to be able to install the winch on skidding lanes. Fig. 2 shows the winch fastened with ground anchors and tied to a tree.

The deceleration of the forwarder is controlled by a feed forward control. The forces acting on the brake disc are increased until the forwarder is not able to pull out the rope any more. Afterwards the pressure on the brake is reduced until the machine is able to drive without interference. Both for the pressure increase as for the decrease, a rate of 0.15 bar/s was chosen. This slew rate was the result of several pretests to get the optimum between a smooth increase of the required traction force and the distance travelled with different rates. 200 m rope and a pulley mounted to the load cell allow between three to seven traction measurements on a single pullout.

Fig. 2 Winch to apply the loads for traction measurements installed on a skidding lane

Slika 2. *Vitlo pomoću kojega se opterećuje stroj prilikom mjerenja trakcije*

During the measurements, the traction force of the forwarder as well as the speed of wheels and above ground were measured on the forwarder. Forces result from a load cell (Hottinger Baldwin Measurements (HBM), model U2B). The speed of the wheels and the effective velocity were determined using incremental rotary encoders (Kübler, model 5800). A modularly equipped measurement system MGCsplit by HBM served as data collector for all applied transducers.

The tests were driven on skidding lanes under different site conditions, which are characterized by high percentage of loess. Apart from soil moisture, the main difference between the site types is the stone admixture. The tests were carried out on bare soil because of the ambiguous effect of a brushwood layer on vehicle traction (Hittenbeck 2004; Jacke et al. 2004). Before the test drives started, all soil parameters like soil type, soil moisture, humus layer and inclination of the stand were determined. In total 57 different test series were taken with 22 different possible factors (Table 1) influencing the traction behavior of the forwarder. Every test run is characterized by the machine configuration (e.g. tracks and chains, unloaded) and stable soil and site conditions. For each of these series, the 22 factors concerning soil and machine parameters were determined and coded into numbers.

Table 1 22 factors considered before the test that can have an impact on traction performance

Tablica 1. *22 čimbenika koji su promatrani prije mjerenja, a za koje se smatra da imaju utjecaja na vučne značajke*

Machine parameters *Značajke vozila*	Site conditions *Uvjeti radilišta*	Soil parameters *Značajke tla*
Tires *Gume*	Site *Radilište*	Water content *Vlažnost tla*
Inflation pressure *Tlak u gumama*	Slope *Nagib*	Soil type *Tip tla*
Wheel chains *Lanci*	Cross slope *Poprečni nagib*	Skeletal admixture *Udio skeleta*
Bogie tracks *Polugusjenice*	Tree species *Vrsta drva*	Humus occurrence *Pojavnost humusa*
Load *Teret*	Skid trail *Vlaka*	Humus type *Vrsta humusa*
		Shear strength *Posmična čvrstoća*
		Sand content *Udio pijeska*
		Silt content *Udio praha*
		Clay content *Udio gline*
		Bulk density (skid trail) *Gustoća tla (u kolotrazima)*
		Bulk density (between trails) *Gustoća tla (između kolotraga)*
		Bulk density (stand, untouched) *Gustoća tla (negaženo tlo sastojine)*

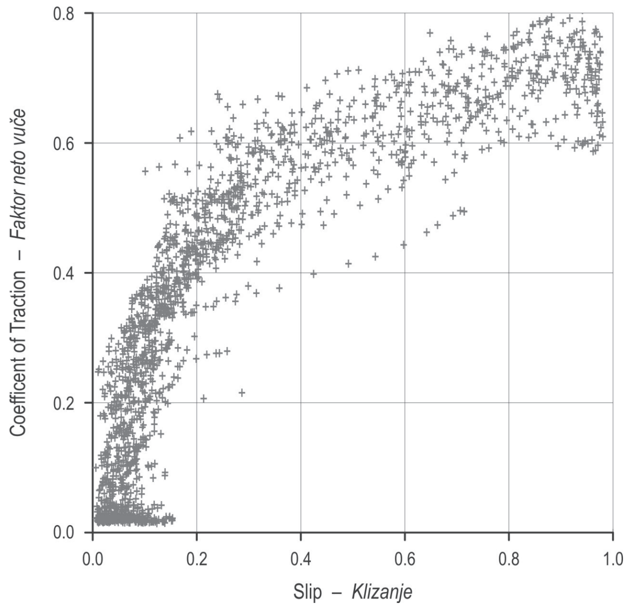

Fig. 3 Traction coefficients over slip measured for the forwarder equipped with tracks and chains at 32.1% soil moisture content on loess soil

Slika 3. *Odnos faktora neto i klizanja forvardera opremljenoga polugusjenicama i lancima na prapornom tlu s 32,1 % vlage*

3.2 Traction – *Trakcija*

The scatter plot in Fig. 3 is an example of the resulting coefficients of traction dependent on wheel slip. It displays the results of traction measurements with tracks and chains (chains were mounted on the front axle and tracks on the rear axle) on loess soil at a soil moisture content of 32.1%. The illustrated data are already revised by artifacts which for example result when the brake of the winch is released and the machine starts driving. In this situation higher slip values can occur although the force to pull the rope is rather low. More detailed information about the data processing can be found in Hittenbeck (2009). With increasing wheel slip, the values of the traction coefficient rise immediately up to a level of about 30% slip. Above that, the increase of the traction coefficients is still clear but less rapid. No maximum value has been specified for the coefficients, although it is often assumed for off road conditions (Moore 1975).

The scatter plot in Fig. 3 is typical for measurements at good traction conditions. The latter are characterized by dry soil conditions or tests with traction aids (tracks and/or chains). Beside this typical (for the conducted tests) shape of the scatter plot, there are other two different types. At higher soil moisture contents and without traction aids, the traction coefficients often culminated between 50% and 80% slip, whereas for poor traction conditions (wet soil, no traction aids, low soil strength) the scatter plots show a smooth increase of traction coefficients over slip which result in comparatively low maximum values.

3.3 Prognosis of Grade Ability – *Procjena razreda kretnosti po nagibu*

For a given slip level (for example the 25% from Söhne /1952/), a wide range of coefficients of traction were measured (Fig. 3). Therefore, it is not plausible to identify an explicit limit resulting from the measure-

Table 2 Regression coefficients for determination of soil ecological inclination limits
Tablica 2. *Regresijski koeficijenti za određivanje ekološke granice nagib*

Variable *Varijable*	Regression coefficient *Regresijski koeficijent*	Standard Error *Standardna pogreška*	*p*-value *p-vrijednost*
Constant – *Konstanta*	29.753	1.416	0.000
Soil water content (–30%) *Vlažnost tla (–30 %)*	–0.831	0.123	0.000
Skeletal rate (0; 1; 2) *Kamenitost (0; 1; 2)*	6.185	1.115	0.000
Tracks (Dummy variable) *Polugusjenice (dummy varijabla)*	7.579	2.663	0.007
Chains (Dummy variable) *Lanci (dummy varijabla)*	6.035	3.283	0.072

Dummy variable: 1 – mounted; 0 – dismounted
Dummy varijable: 1 – postavljene; 0 – nepostavljene

Table 3 Regression coefficients for determination of maximum inclination limit
Tablica 3. *Regresijski koeficijenti za određivanje maksimalnoga nagiba*

Variable *Varijable*	Regression coefficient *Regresijski koeficijent*	Standard Error *Standardna pogreška*	*p*-value *p-vrijednost*
Constant – *Konstanta*	47.530	1.180	0.000
Soil water content (–30%) *Vlažnost tla (–30 %)*	–0.583	0.103	0.000
Skeletal rate (0; 1; 2) *Kamenitost (0; 1; 2)*	4.766	0.929	0.000
Tracks (Dummy variable) *Polugusjenice (dummy varijabla)*	9.790	2.219	0.000
Chains (Dummy variable) *Lanci (dummy varijabla)*	9.438	2.735	0.001

Dummy variable: 1 – mounted; 0 – dismounted
Dummy varijable: 1 – postavljene; 0 – nepostavljene

ments. This can be resolved by adjusting a suitable regression model for the progression of the coefficients of traction above wheel slip. As there were different outlines of the scatter plots due to different traction conditions, which sometimes showed a maximum but most often missed one, a cubic regression model was applied. For the resulting 57 models, the traction coefficient (and therefore the resulting inclination through multiplication with 100) at 25% slip was calculated. These values served as command variable for a stepwise linear regression with the possible influence factors on traction behavior. The test conditions are coded by 22 different variables that describe the characteristics of the test stand, machine parameters and soil conditions. Table 1 gives a list of the variables related to the three main categories. From these factors (22 in total), soil water content and skeletal admixtures (grouped into 3 subclasses) as well as the application of traction aids (tracks and/ or chains) were identified by a stepwise linear regression as main parameters to traction behavior. The subclasses to skeletal admixtures in the topmost 20 cm were: free of skeleton (group 1), up to 7% skeletal admixture (group 2) and admixtures above 7% (group 3).

Table 4 Inclination limits resulting from regression models for loess soils
Tablica 4. *Granični nagib regresijskoga modela za praporna tla*

Soil-Water-Content (skeletal rate) *Vlažnost tla (kamenitost)*	Wheels – *Kotači*		Tracks and Chains – *Polugusjenice i lanci*	
	Inclination limit (ecological) *Granični nagib (ekološki)*	Inclination limit (max.) *Granični nagib (maksimalni)*	Inclination limit (ecological) *Granični nagib (ekološki)*	Inclination limit (max.) *Granični nagib (maksimalni)*
%				
25 (0)	34	50	48	70
30 (0)	30	48	43	67
35 (0)	26	45	39	64
40 (0)	21	42	35	61
45 (0)	17	39	31	58
%				
25 (<7)	40	55	54	74
30 (<7)	36	52	50	72
35 (<7)	32	49	45	69
40 (<7)	28	46	41	66
45 (<7)	23	44	37	63
%				
25 (>7)	46	60	60	79
30 (>7)	42	57	56	76
35 (>7)	38	54	52	73
40 (>7)	34	51	47	71
45 (>7)	30	48	43	68

The resulting regression model is presented in Table 2. The constant describes the theoretically accessible grade (limit) with 25% wheel slip at a soil water content of 30% for the forwarder without tracks and chains. The expected negative influence of soil moisture on traction behavior and therefore the ability to climb slopes is indicated by the regression coefficient for the soil water content. An increase of soil water content of 1 Vol-% reduces the prognosis of trafficable grade by 0.83 grade percent. All the other factors enhance the prognosis of grade ability for the forwarder. Changing the skeletal content of the top soil layers to one of the two superior subclasses (free of skeleton; up to 7%; over 7%) resulted, based on the measured data and the conducted linear regression, in an increase of the prediction (from the regression model, all other conditions remaining equal) of 6.2 grade percent. The skeletal content is divided into subclasses for practical application of the whole model. The regression coefficients for the traction aids sum to 13.614 and point at the positive impact on traction ability.

Besides the grades accessible with an accepted level of wheel slip, the maximum inclinations that assure stability against sliding downhill are a question of practical relevance, and especially in cases where the mobility of machines in grades is assisted by a traction support winch (Forbrig et al. 2004; Nick 2005; Stuhlmann and Findeisen 2009). These techniques serve to extend the highly mechanized harvesting into slopes that cannot be traveled on according to the own drive line abilities or just with serious damages to the soil. In the light of safety for the machine operator and machine, it has to be assured that in case of a rope crack or technical problems the machine is able to stand without gliding. Limits depending on soil properties could be calculated similar to the already presented limits from the maximum values of the regression models. Since these models often lack a maximum or the values are not covered by measured data, another possibility was used. The measured data were assigned to one of ten groups of wheel slip, which are distributed evenly over the slip range from 0% to 100%. Data with < 10% slip were related to the first group, 10% < 20% to the second and so on. The average values of the traction coefficient were calculated for all of the 57 test series in every group. The maximum (average value) in each case (test series) served again as dependent variable of a linear regression. The resulting regression model is presented in Table 3.

On the basis of the presented regression models, trafficable grades can be estimated depending on soil properties and machine facilities. Table 4 presents the resulting ecological (max. 25% slip) and maximum (safety against sliding) inclination limits for a forwarder on loess soil for a wide range of soil water contents. At the same time, distinction is made between the application of traction aids (tracks and chains) and the use of the forwarder just on wheels. For good weather conditions with low soil water contents even grades up to 34% seem trafficable uphill with a maximum of 25% wheel slip (ecological limit). Under the same conditions the model assumes stability against sliding up to longitudinal inclinations of 50%. When soil moisture increases, the trafficable grades are reduced for example to 21% inclination at 40% soil water content. Notably higher slope angles can be climbed with the machine when tracks and chains are mounted as well as when the top soil layer offers an increased skeletal rate.

3.4 Validation – *Provjera modela*

Table 4 presents inclination limits for loess soils calculated on the theoretical assumption of confrontation of traction force and downhill slope force. Although it works in theory, there is no proof that »off road« reality sticks to the theory. In order to answer that question, validation measurements in inclined terrain were taken parallel to the traction tests. The aim of these measurements was to verify the ecological inclination limits due to a maximum of 25% wheel slip. Tests persist of trial drives up hill on steady slopes between 11% and 40%. The aim of the test was not to investigate the maximum limits assuming stability against gliding, as such investigation would be too dangerous.

During the tests, slip was measured and reduced to average and maximum values for further considerations. The aim was not to verify a precise prognosis of the wheel slip level but to make comparison with the limits calculated from the model presented in Table 4. For every trial drive in inclined terrain, it was checked if mobility of the machine was possible with less than 25% slip from the model as well as from the observed average values. For 19 out of 31 validation tests, the inclinations seemed trafficable with no more than 25% wheel slip. Only one of these tests led to an average slip just above that limit. Driving at inclinations above the limit calculated from the model resulted in seven cases clearly exceeding the slip limit. One test series led to an average slip level of well below 25%, whereas the maximum slip clearly exceeded that level. Four test series showed unexpected good traction for the forwarder so that driving uphill was possible without exceeding the slip limit of 25%.

4. Discussion – *Rasprava*

The validation tests for the ecological limits showed that the prognosis (trafficable with ≤ 25% slip) matched the reality for over 80% of these tests. The maximum inclinations of the model were not tested. However, the validation test stated that the maximum inclinations from the model are not trafficable by driving uphill, which was expected. Anyhow the resulting maximum inclination values might be used for the question of limitations for machinery working downhill and for machines with traction support winches. Both should only be done or used in areas where the stability of the machines against gliding is assured.

In the light of various factors that influence traction abilities and mobility in grades, the present approach of calculating limits for inclinations indicates a fairly good agreement between the model and validation tests. When evaluating the model, it has to be kept in mind that it was developed especially for loess soil. These are for example widespread in the temperate zone in Europe (and here typical for the middle mountain ranges in Germany, where the tests were conducted) or the Midwestern United States (Haase et al. 2007). The focus on loess soils limits the scope of validity of the present models.

With increasing soil water content in loess soils, the interaction between soil and drive line of the machines changes. Under rather dry conditions, the frictional properties regarding the Mohr-Coulomb failure criterion (Wong 2010) of the soil dominate, while the cohesive part is marginal. For these conditions shear strength of the soil and hence also traction force depends on the internal shearing resistance of the soil material and the normal force acting on the soil. In wet loess soils the cohesive properties dominate so that the possible traction force depends on the contact area and the cohesion of the terrain (Wong 2010). It is then independent of the normal force (under flat conditions the weight (in N)). This however conflicts with equation 2, where it is assumed that traction force is the result of normal force and coefficient of friction. For a wide range of trafficable soil, it can be expected that the frictional properties of the soil dominate and therefore equation 2 can be seen as a justifiable simplification. In addition, the traction force was measured at varying soil water contents in order to calculate the traction coefficient by division with weight of the machine. For solving the question of calculating the inclination limits, it could be assumed that the measurements compensate the main errors made by the theoretical traction equation (2) used.

Even though the present model gives appropriate inclination limits, it has to be kept in mind that working at the limits of machine trafficability is not just a matter of soil conservation and timber mobilization but also stress for the operator. Most of the machines used in steeper terrain are not equipped with tilt facilities, which allow a relaxed positioning of the operator. Harvesters are often provided with tiltable cabins but there are very few forwarders equipped with tiltable driver seats. This results in ergonomic stress (Lambert and Howard 1990; Heinimann 1999) for the operator. Apart from the physical strain, there are psychic stresses related to increased risks and higher requests for the operation because of the reduced handling opportunities. In order to ease the harvesting and forwarding operations in steep terrain, the machines that are regularly used for inclined areas should be equipped with tiltable cabins or driver seats and cranes. This would reduce the physical strain for the operator and in case of a tiltable boom the damages to the residual trees would be reduced.

5. Conclusion – *Zaključak*

Even with the mentioned inaccuracy, the approach of calculating trafficable inclinations from measurements of traction force and slip leads to a good prognosis. The resulting model for grade ability on loess soils indicates that a soil conserving highly mechanized harvesting is possible in a wide range of inclination angles. However, it should be taken into consideration that the resulting limits from the model are based on the soil properties. Therefore, highly mechanized harvesting in inclined terrain should be linked to dry weather conditions or to the application of traction aids to allow the requested mobility on grades. For rather unfavorable soil conditions (skeletal free, 40% soil water content) the present inclination model results in an ecologically trafficable inclination of at least 20%. Under the same conditions, a machine equipped with tracks and chains is able to climb inclinations up to 35%. For both examples, however, it has to be noticed that the bearing capacity of the soil is already reduced. Considerable soil compaction effects could be expected. It should be emphasized that machine traffic has to be reduced to dry and favorable weather conditions, especially in inclined terrain, in order to reduce the damage to the soil and hence to ensure the long-term trafficability.

Harvesting operations in a terrain with more than 20% inclination should therefore be supported early enough by traction aids (tracks and/or chains). This improvement of soil protection (Kremer et al. 2007) and safety for the operator is the result of damages done to the root system of the trees at the skidding lane edge (Schardt et al. 2007) and of increased machine weight (Jacke 2007). In addition, there are different types of tracks that are optimized for special operation conditions and therefore differ in their ground pressure and traction abilities.

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Sažetak

Procjena razreda kretnosti na nagibu na temelju vučne značajke forvardera

Drvo kao obnovljivi resurs postaje sve zanimljiviji kao materijal, ali i kao izvor energije. Kako bi se udovoljilo potrebama za drvom, potrebno je da se dosad neiskorištene količine drva učine dostupne tržištu. Zbog toga je sve više zanimanja za nedovoljno iskorišteno drvo na nagnutim terenima. Nagnutost terena vrlo je važan ograničavajući čimbenik koji sprječava upotrebu potpuno visoko mehaniziranih sustava pridobivanja drva i koji smanjuje stabilnost vozila pa vozila čine štetu na tlu.

Utjecaj horizontalne sastavnice težine forvardera (F_T na slici 1) upućuje na izravnu povezanost stupnja nagiba i faktora neto vuče. U teoriji se čini mogućim izračunavanje razreda kretnosti na nagibu za prihvatljivo proklizavanje kotača ili izračunavanje graničnoga nagiba pomoću najveće trakcije. Na osnovi odabrane granične vrijednosti klizanja od 25 % razvijen je i testiran model određivanja razreda kretnosti na nagibu.

Mjerenja faktora neto vuče obavljena su na prapornom tlu, na forvarderu Ponsse S 10. Za potrebe istraživanja konstruirano je dinamometarsko vitlo koje je služilo za mjerenje vučne sile pri kretanju neopterećenoga forvardera, pa sve do sila koje su prelazile mogućnosti istraživanoga vozila. Nadalje, kako bi se ispitala pouzdanost razvijenoga modela, provedena su istraživanja, bez upotrebe vitla, na nagnutom terenu uz ograničavanje klizanja na 25 %. Za poboljšanje kretnosti vozila na nagibu često se upotrebljavaju polugusjenice i lanci pa su zbog toga provedena istraživanja uz dva različita tlaka punjenja u gumama, pri različitim vrstama tovara te usporedbom novih i istrošenih guma. Tijekom istraživanja prikupljeni su podaci o samom mjestu istraživanja, kao što su vlažnost tla, kamenitost terena, gustoća tla, debljina humusnoga sloja i vrsta drveća (zbog različitih korijenskih sustava).

Mjerenja vučne sile nasuprot klizanju istaknula su vlažnost tla i kamenitost terena kao glavne značajke tla koje utječu na mogućnost kretanja strojeva uz nagib. Što se tiče značajki samoga stroja, razlika između guma i tlaka punjenja u gumama ima mali utjecaj, ali upotreba polugusjenica i lanaca značajno povećava trakciju te samim time i mogućnost kretanja forvardera uz nagib. Stoga je procjena razreda kretnosti obavljena na osnovi značajki tla (vlažnosti tla, kamenitosti) i upotrebe polugusjenica i lanaca.

Testne vožnje na nagnutom terenu pokazuju da se računanjem ograničenja razreda kretnosti na osnovi istraživanja vučne sile na ravnom terenu dobiju zadovoljavajući rezultati. Provjerom rezultata dokazano je da preko 80 % proračuna, za klizanje ≤ 25 %, odgovara stvarnim uvjetima. Najveći mogući nagib proračunat u modelu nije testiran.

No, kako je i očekivano, prekid je kretnosti dosegnut puno prije nego što predviđa model na osnovi maksimalnih faktora neto vuče.

Čak i uz neke netočnosti, pristup računanju razreda kretnosti na nagibu preko mjerenja vučne sile i klizanja daje dobre rezultate. Razvijeni model pokazuje da je upotreba okolišno pogodnih mehaniziranih sustava pridobivanja drva moguća na različitim nagibima. Bitno je naglasiti da je osobito na nagnutim terenima kretanje šumskih strojeva dopušteno samo pri suhom i lijepom vremenu kako bi se smanjili negativni utjecaji strojeva na šumsko tlo te tako osigurala dugoročna prohodnost. Faze mehaniziranoga pridobivanja drva na nagibima većim od 20 % trebale bi se izvoditi uz upotrebu polugusjenica i lanaca.

Ključne riječi: mehanizirano pridobivanje drva, nagib, prapor, klizanje kotača, model

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